National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Atmospheric Infrared Sounder

Middle Strat (25km) and Lower Trop (2.2km) CO2 from AIRS (progress toward satellite retrieval of a profile)

Mous **Chahine**, Edward Olsen, Luke Chen, Tom Pagano,
Xun Jiang and Yuk Yung

NOAA Hyperspectral Spectrometer Workshop

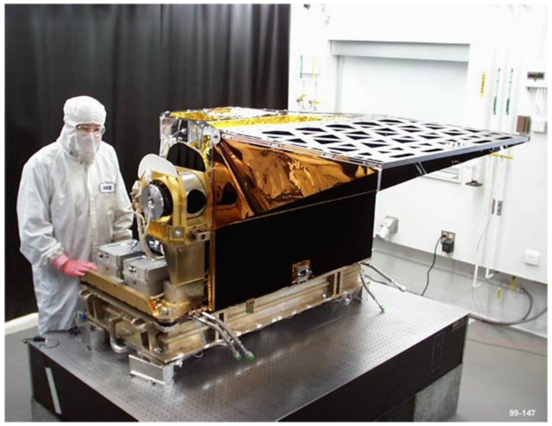
March 29 - 31, 2011

Miami Florida

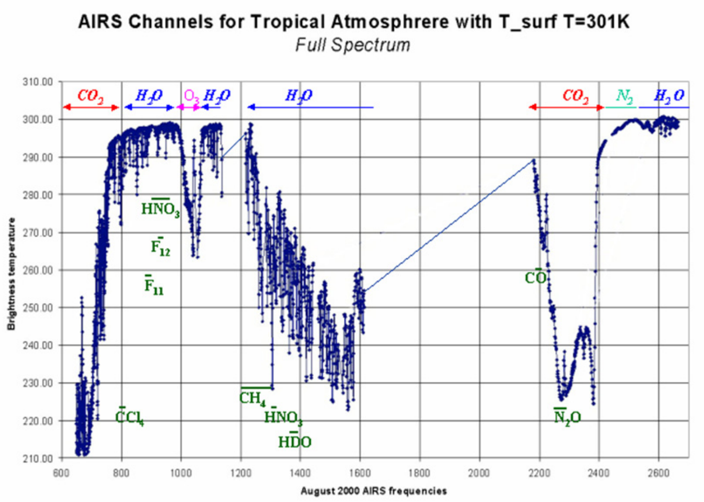
The Atmospheric Infrared Sounder on NASA's EOS Aqua Spacecraft

- AIRS Characteristics
- Launched: May 4, 2002
- Orbit: 705 km, 1:30pm, Sun Synch
- IFOV : 1.1° x 0.6°
  (13.5 km x 7.4 km)
- Scan Range: ±49.5°
- Full Aperture OBC Blackbody, $\varepsilon > 0.998$
- Full Aperture Space View
- Solid State Grating Spectrometer
  - IR Spectral Range:
    3.74-4.61 µm, 6.2-8.22 µm,
    8.8-15.4 µm
  - IR Spectral Resolution:
    ≈ 1200 ($\lambda/\Delta\lambda$)
  - # IR Channels: 2378 IR
- VIS Channels: 4
- Mass: 177Kg,
  Power: 256 Watts,
  Life: 5 years (7 years goal)
- Built: BAE Systems

AIRS



AIRS Spectra

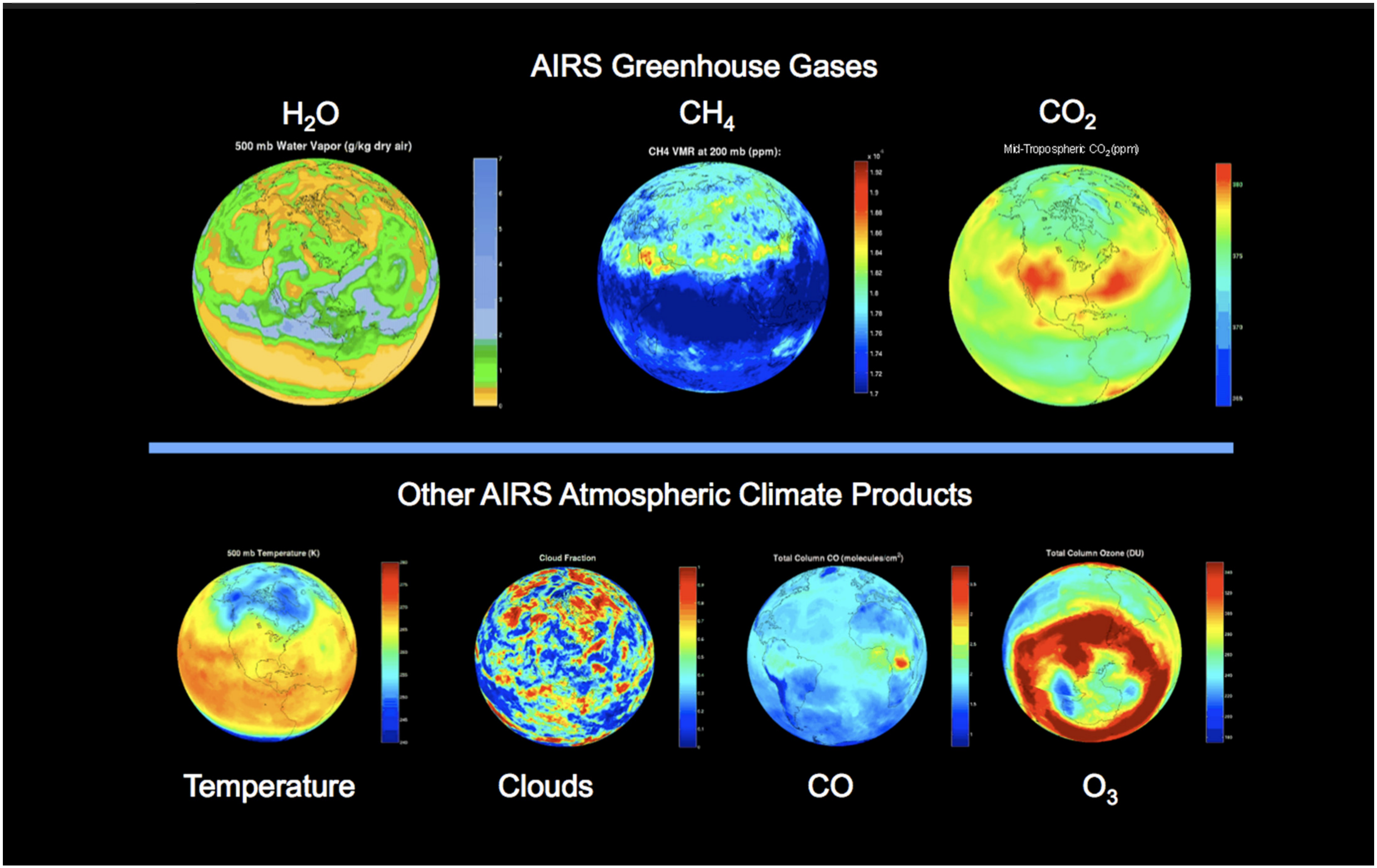


National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Atmospheric Infrared Sounder

AIRS Products for Weather, Climate and Composition



3 Layers of CO_2 Derived from AIRS

Current Status

Task	Mid-Troposphere	Stratosphere	Lower Troposphere
Algorithm Development Initial Channel Selection	✔	✔	✔
Retrieval Optimization Beta Software Development & Test Refine Channel Selection Refine Quality Control	✔	✔	✔
Validation and Comparison In-Situ Measurements Models	✔*	In progress	In progress
Report Results Professional Meetings Journal Publications	✔		
Transition to Operational Stage Production Software Development Documentation	✔		
Production	✔		
Distribution via GES DISC & JPL	✔*		

Continuous Updates

The Method of Vanishing Partial Derivatives Finding the LOCAL minimum on an N-Dimensional Surface According to Gauss

The CO_2 retrieval is a post-processing algorithm applied after AIRS Level-2 product generation:

Local Minimum: $\Theta_M,\ T^0(p),\ q^0(p),\ O_3^0(p),\ E_s^0(v)$

$$\frac{\partial G}{\partial X_{CO_2}} \to 0$$

$$\frac{\partial G}{\partial X_{T(p)}} \to 0$$

$$G^{(n)}(\mathbf{X}) = \sum_{\nu}\left[\Theta_M(\mathbf{X},\nu) - \Theta_C^{(n)}(\mathbf{X},\nu)\right]^2$$

$$\frac{\partial G}{\partial X_q} \to 0$$

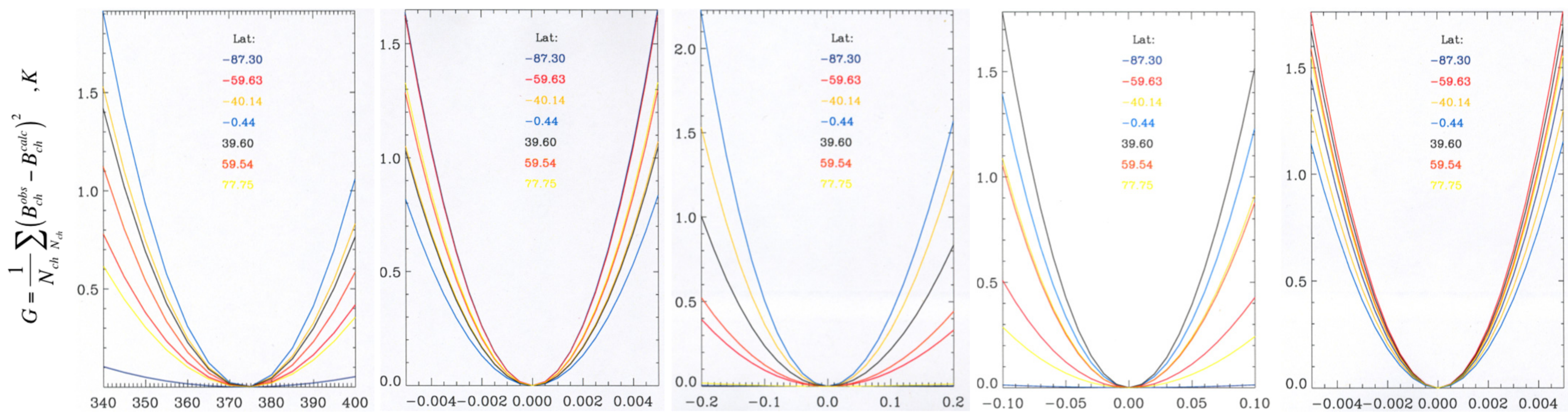
$$\frac{\partial G}{\partial X_{O_3}} \to 0$$

$$\frac{\partial G}{\partial X_{E_s}} \to 0$$

Satisfying the partial derivatives individually provides the necessary and sufficient condition for an *extremum* of *G*(X). Ascertaining that the extremum is a (local) *minimum* is the result of requiring that G decreases monotonically with each iteration.

Caveats: X_i are assumed to be independent variables, the completeness of the variable set, the minimum found is not global, and the non-commutative averaging of variations of the variables within data pixels does not lead to significant errors

The Local Minimum is Well Defined



CO_2 (ppm)

Air Temperature Fractional Change

Water Vapor Fractional Change

Ozone Fractional Change

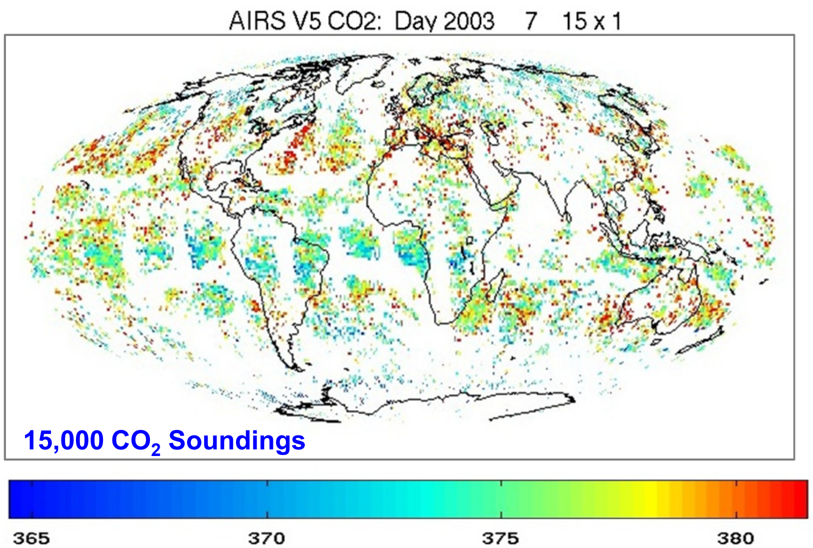
Surface Emission, E_s Fractional Change

Reference: M. Chahine, C. Barnet, E. T. Olsen, L. Chen and E. Maddy ""On the Determination of Atmospheric Minor Gases from the Residuals of the Solution of the Radiative Transfer Equation". Journal of Geophysical Research Letters, Vol. 32, November 2005.

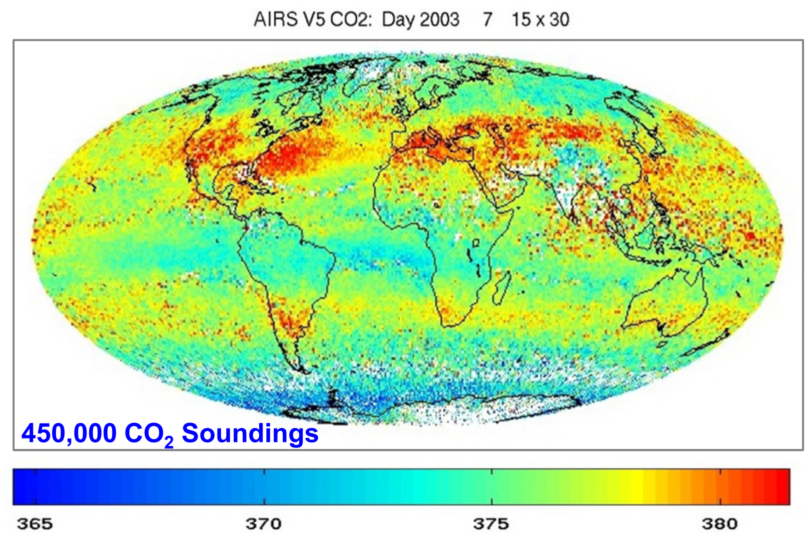
AIRS Operational Product
Mid-Tropospheric CO_2
(8-10km)

Global Yield of AIRS Level 2 Mid-Tropospheric CO_2

AIRS Daily CO_2 Yield
1°x1° Spatial Resolution



AIRS Monthly CO_2 Yield
1°x1° Spatial Resolution



AIRS Level 2 Mid-Tropospheric CO_2 retrieval yield is controlled by requirement for highest quality temperature and water vapor AIRS Level 2 products in 2x2 array of adjacent FOVs

Day/Night, Pole-to-Pole, Land/Ocean/Ice, Cloudy/Clear

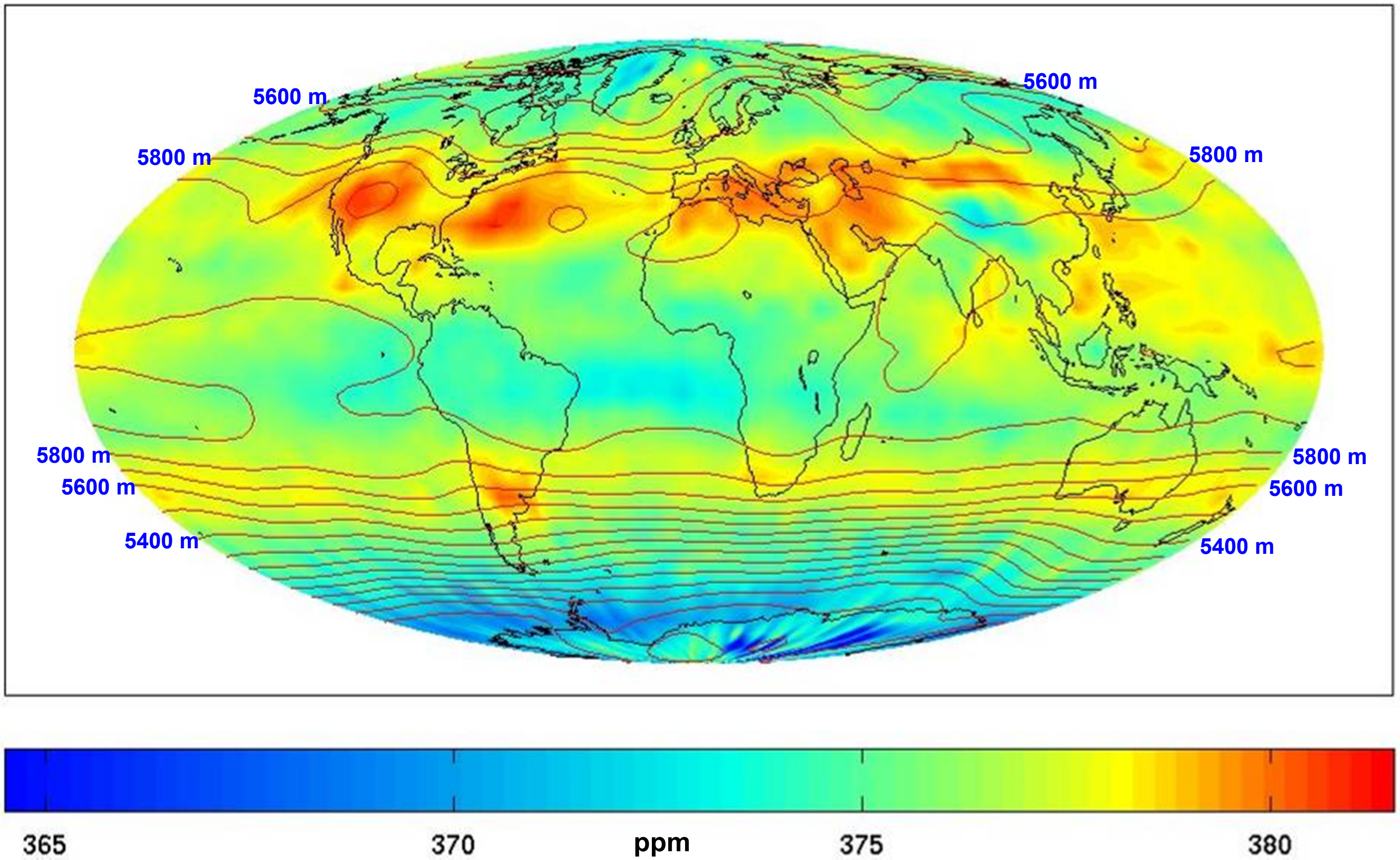
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Atmospheric Infrared Sounder

AIRS Data Show
CO_2 is not well mixed in Mid-Troposphere

July 2003 AIRS mid trop CO_2 (5° smoothing) with 500 hPa gph contours

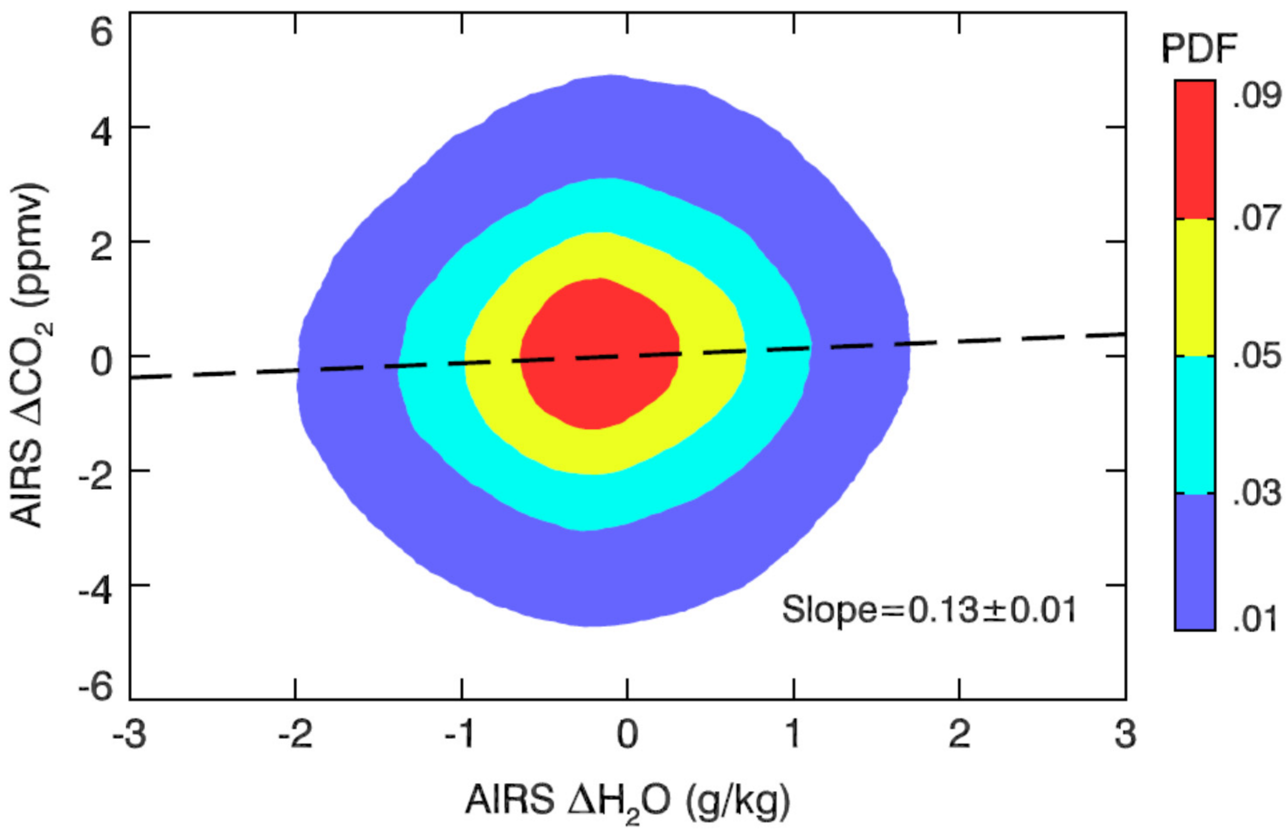


CO_2 is <u>NOT</u> Well Mixed in the mid-troposphere
- **Driven by synoptic-scale phenomena (polar/subtropical jet streams)**
- **Complexity of the Southern Hemisphere not present in models**
- **AIRS mid-trop data will facilitate modeling of vertical & horizontal transport**

Small Bias due to H_2O Absorption

- **If MJO Amplitude of H_2O at 600 hPa ≈ 1.4 g/kg**
  [*Tian et al. (2006)*, Vertical moist thermodynamic structure and spatial-temporal evolution of the MJO in AIRS observations, J. Atmos. Sci., 63, 2462]
- **Then Potential Bias in CO_2 ≈ 1.4 × 0.13 < 0.2 ppm**

Observations between 10° S – 10° N



King-Fai Li, Tian, B., Waliser, D.E. and Yung, Y.L. (2010), Tropical mid-tropospheric CO2 variability driven by the Madden-Julian Oscillation, PNAS, 107 (45), 19171-19175, doi: 10.1073/pnas.1008222107

Lack of Correlation in the AIRS VPD Retrievals Among CO2 ,T, H2O and O3

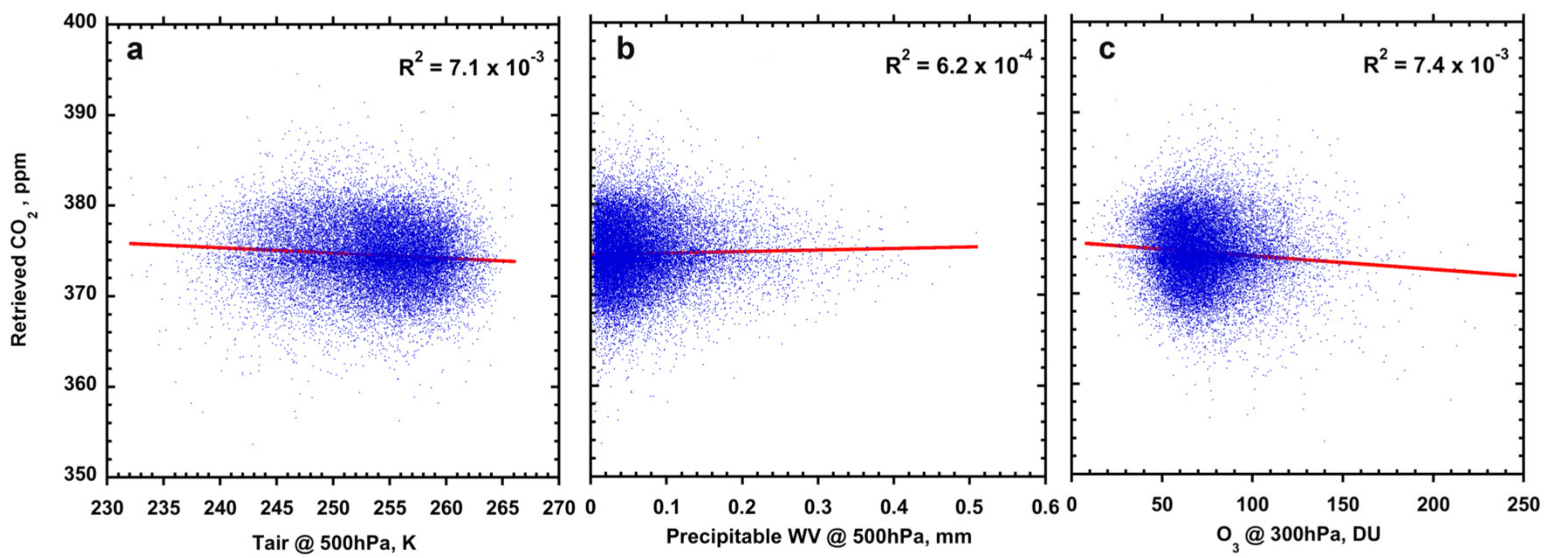
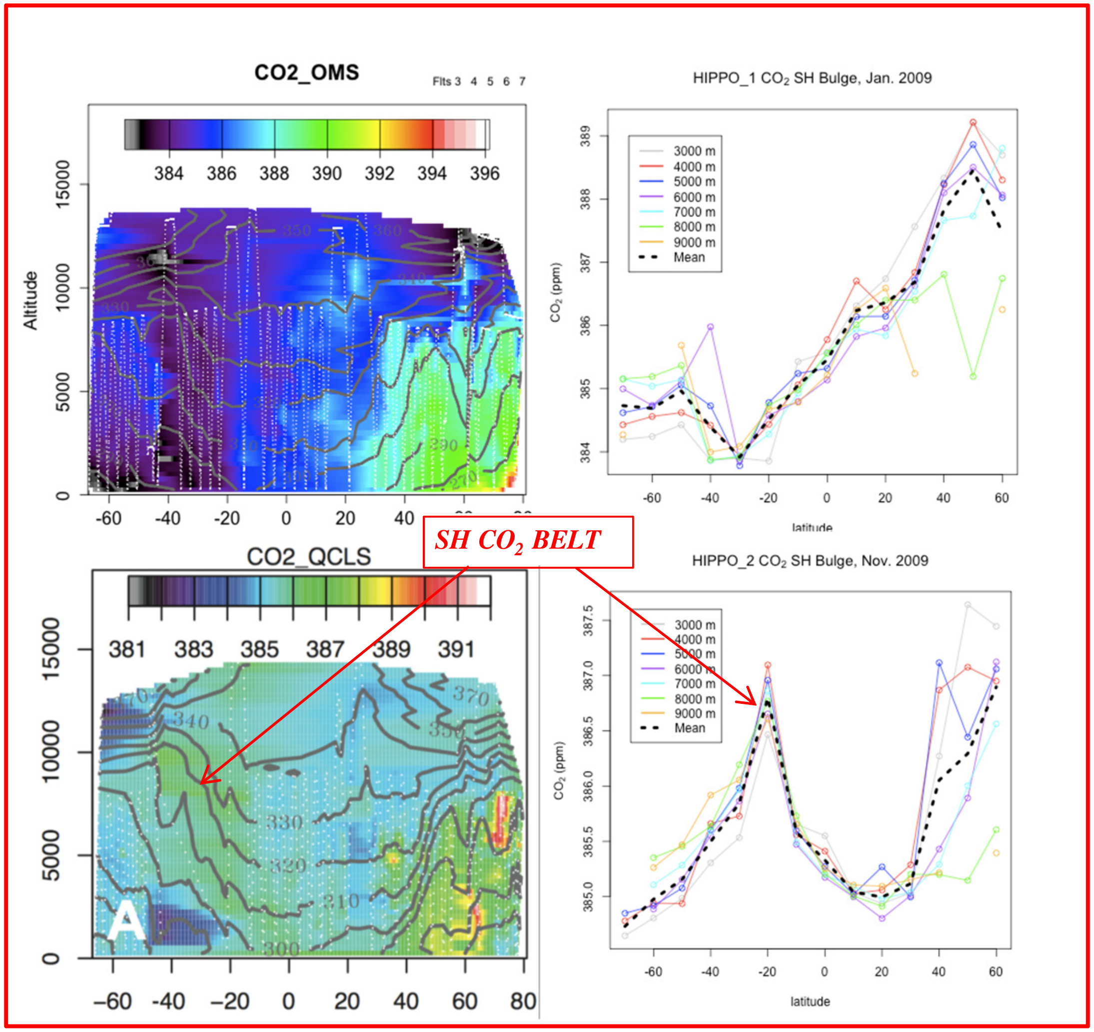


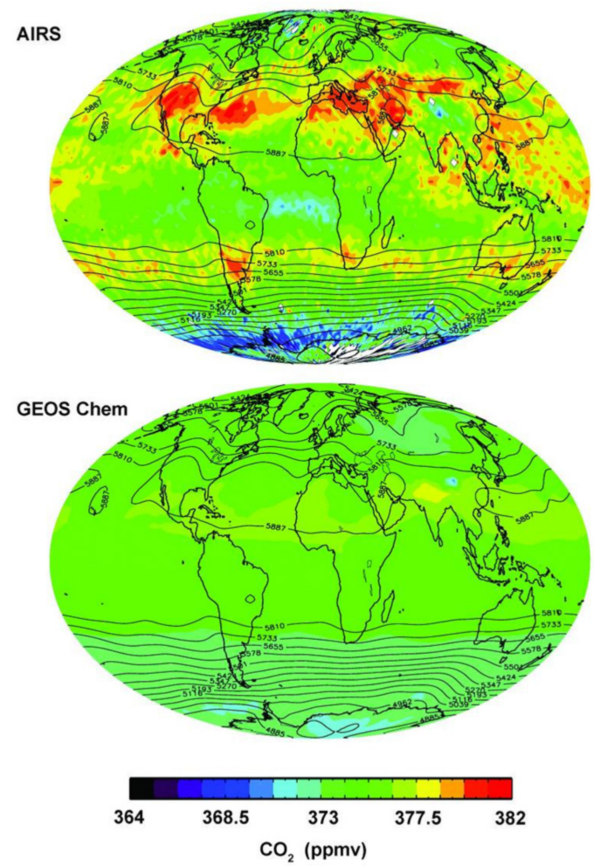
Figure demonstration of lack of correlation among the VPD solutions for 24,635 retrievals of CO_2 and (a) T(500 hPa); (b) H_2O(500 hPa); (c) O_3(300 hPa) during January 2003 in the latitude band 30N to 40N. R^2 represents the portion of the variance in CO_2 that could be explained by the variance in the other parameter and is less than 0.8% in all cases.

Figure generated by Ed Olsen in 2006

Variability seen in 2009 HIPPO Campaign Compares well with AIRS



AIRS has observed a seasonally-variable SH CO_2 Belt Since 2003



S.C. Wofsy, *et al* (2011), HIAPER Pole-to-Pole Observations (HIPPO): Fine grained, global scale measurements of climatically important atmospheric gases and aerosols, *Proceedings of the Royal Society A, in press.*

M.T. Chahine, et al,, Satellite remote sounding of mid-tropospheric CO2, Geophys. Res. Lett., 35, L17807, doi:10.1029/2008GL035022.

AIRS Developing Product
Mid-Stratospheric CO_2
(25km)

National Aeronautics and Space Administration

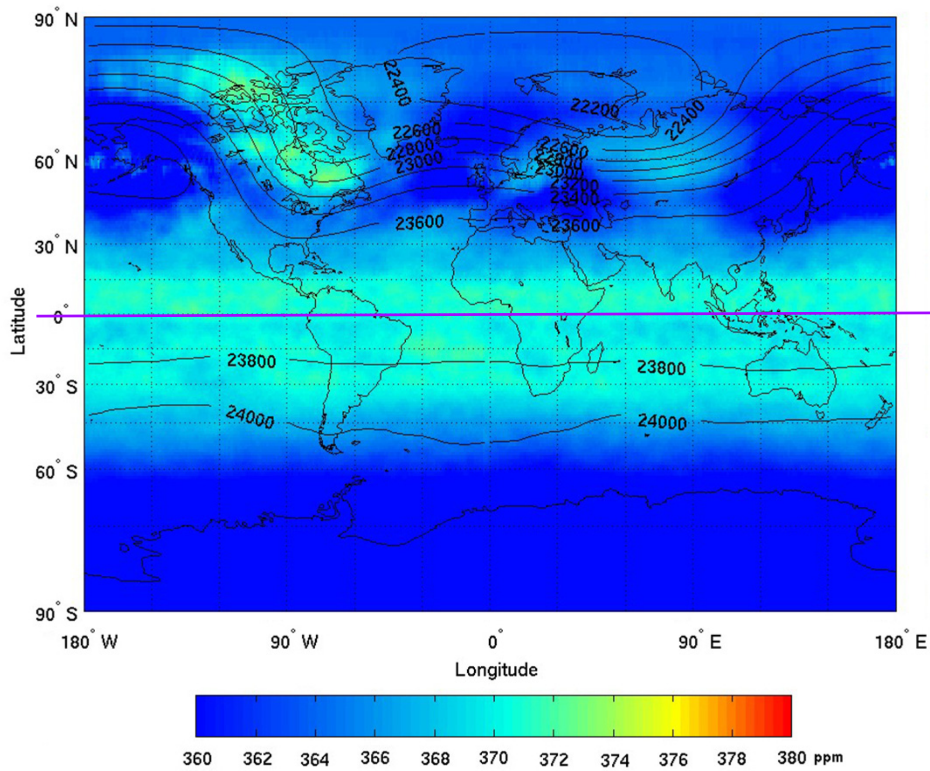
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Atmospheric Infrared Sounder

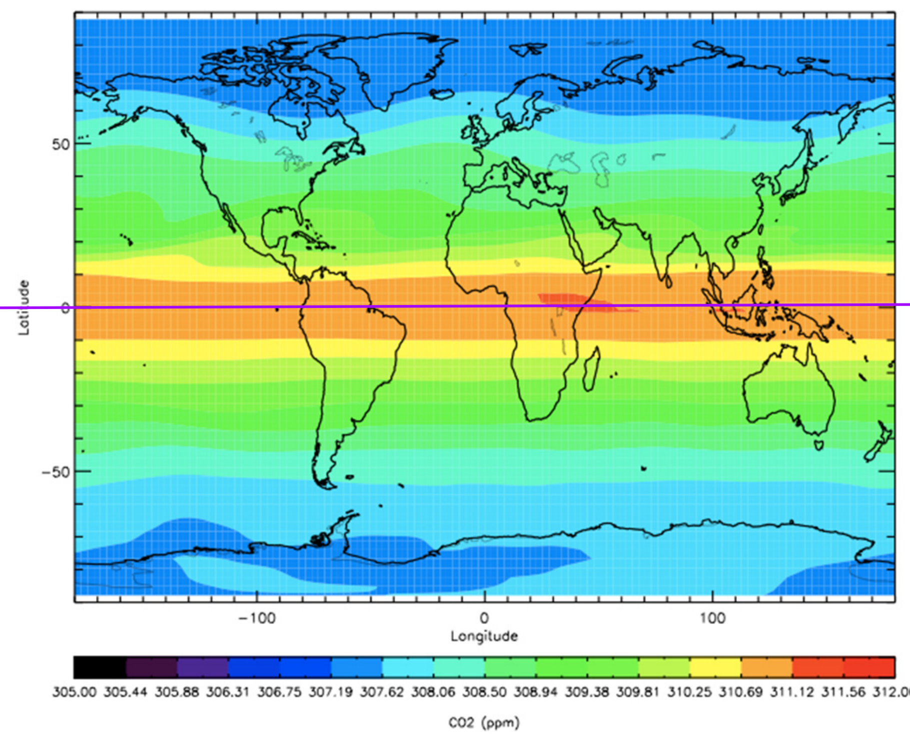
Jan 2003 Stratospheric CO_2 Retrieval Compared to Models

(AIRS Stratospheric Contribution Function Applied to Models)

AIRS Retrieved CO_2



3-D IMATCH CO_2



360 Contours are 30 hPa GPH 380

305 Model profile weighted by AIRS sensitivity function 312

PRELIMINARY

Both AIRS and models show presence of tropical pipe
- **AIRS shows greater variation with latitude (~15 ppm vs ~4 ppm)**
- **AIRS shows additional troposphere intrusion at high latitude**

Model Runs by Xun Jiang, University of Houston

National Aeronautics and Space Administration

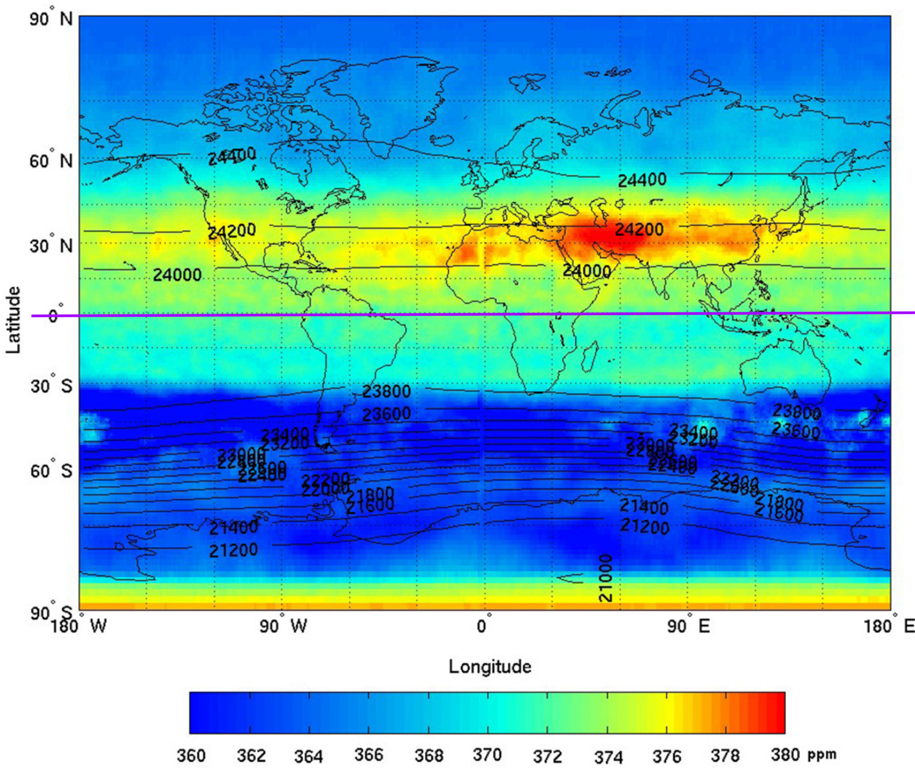
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Atmospheric Infrared Sounder

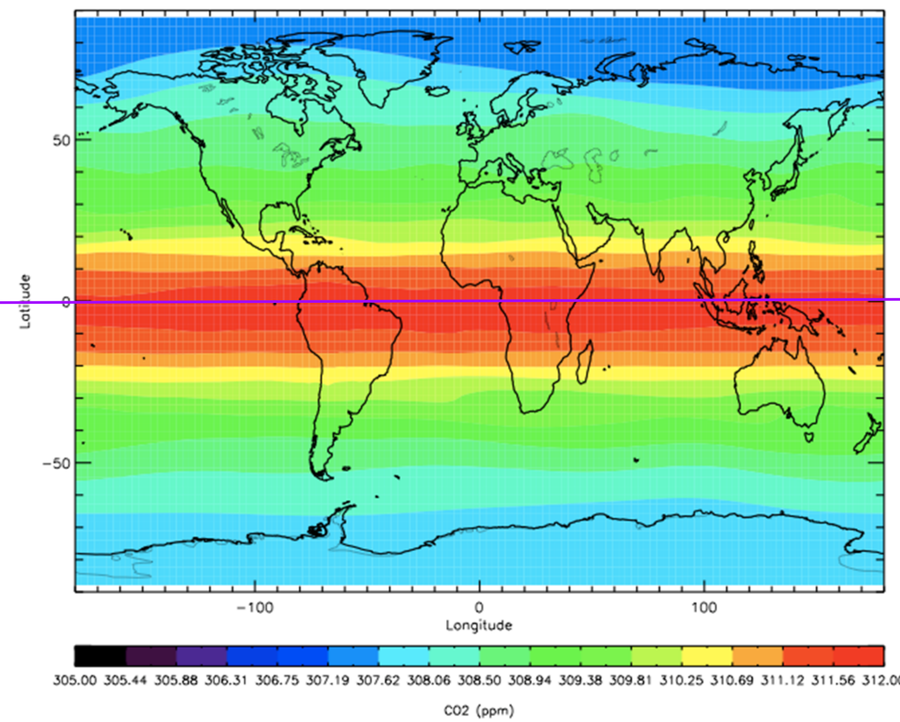
Jul 2003 Stratospheric CO_2 Retrieval Compared to Models

(AIRS Stratospheric Contribution Function Applied to Models)

AIRS Retrieved CO_2



3-D IMATCH CO_2



360 **Contours are 30 hPa GPH** **380**

305 **Model profile weighted by AIRS sensitivity function** **312**

PRELIMINARY

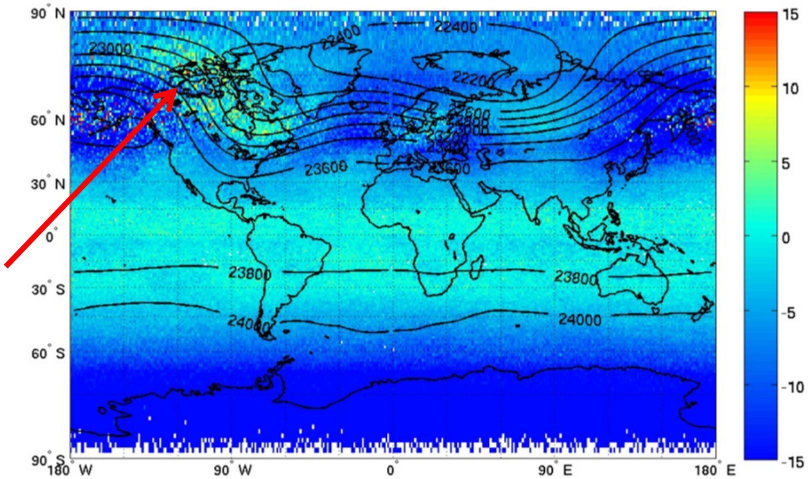
AIRS tropical Pipe shifts northward in July whereas model tropical pipe remains unchanged

- **AIRS shows greater variation with latitude (~15 ppm vs ~4 ppm)**

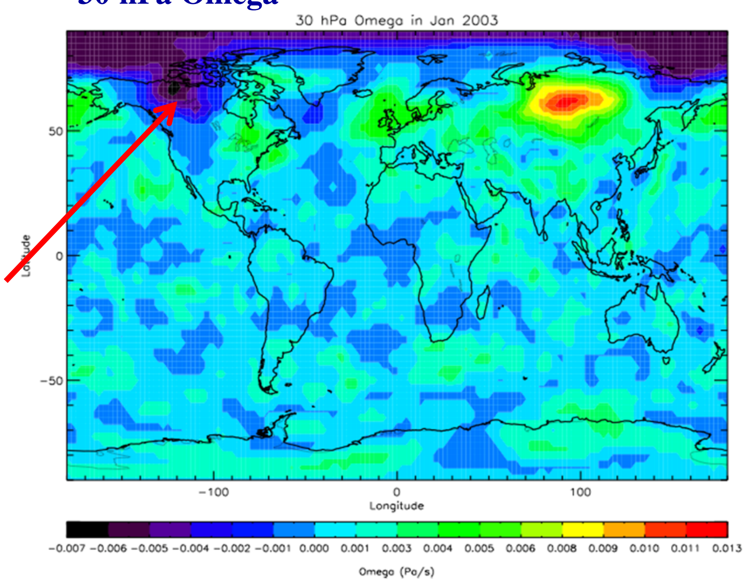
Model Runs by Xun Jiang, University of Houston

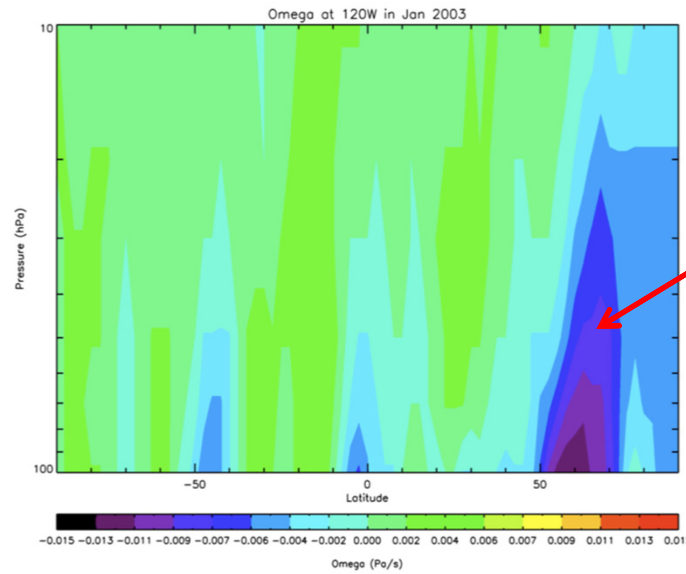
AIRS Stratospheric CO_2 (tropospheric CO2 intrusion/vertical wind)

AIRS CO2 for January, 2003



30 hPa Omega





Vertical velocity (dP/dt) at 120°W in January 2003 (NCEP2 Reanalysis)
Negative (positive) value represents upward (downward) motion. Units are Pa/s.

Omega = dP/dt at 30 hPa (NCEP2 Reanalysis)
Negative Omega --- Upward motion;
Positive Omega --- Downward motion

National Aeronautics and Space Administration

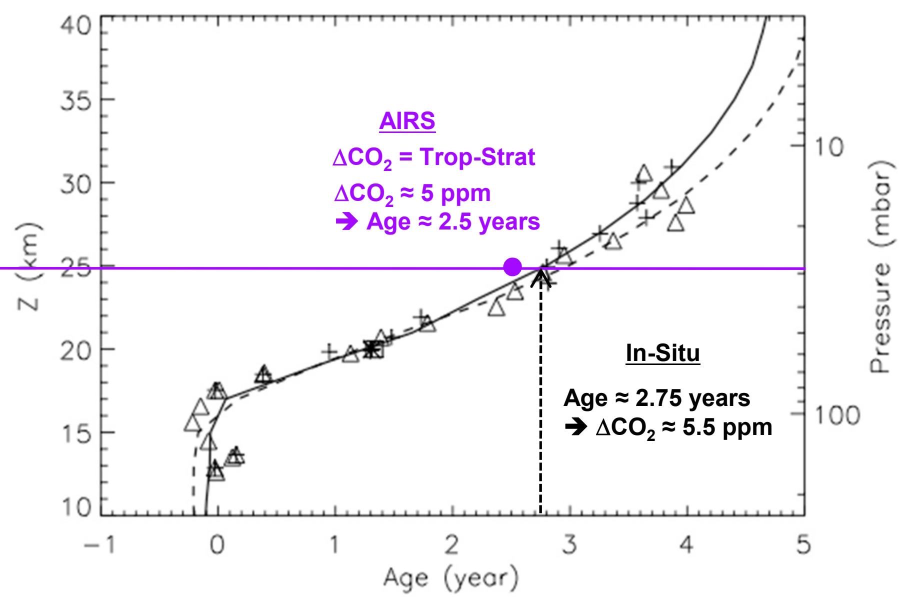
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Atmospheric Infrared Sounder

CO_2 Trop-Strat Contrast due to Age of Stratospheric Air

Hall et al (1999), Evaluation of transport in stratospheric models, JGR., 104, 18815

Altitude of maximum of AIRS Contribution Function

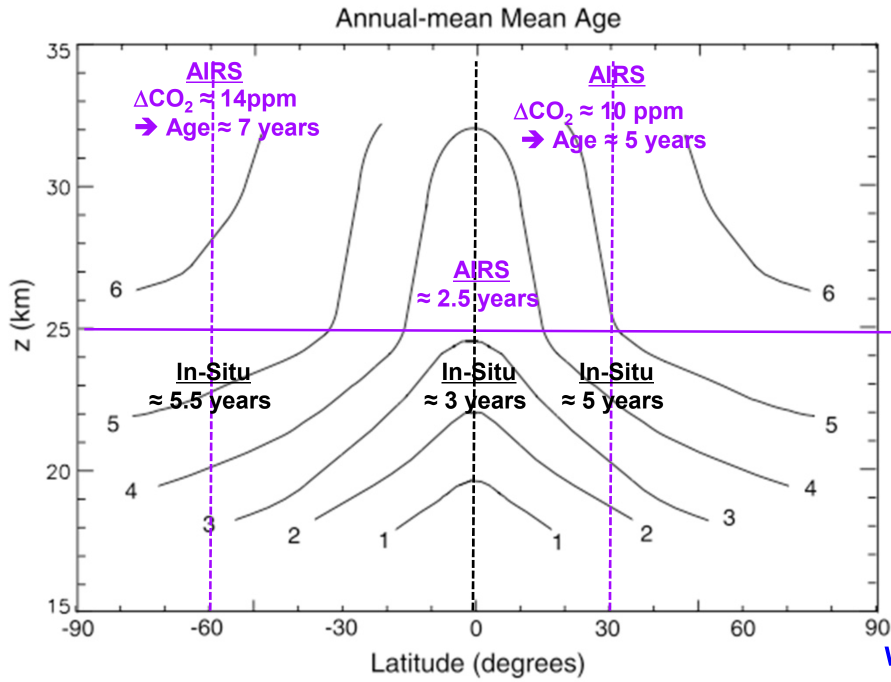


Age of stratospheric air vs altitude for |latitude| ≤ 10°

The concentration of CO_2 in the stratosphere will be lower than in the troposphere by ~ 2 ppm for each year it lags behind due to interannual growth of tropospheric CO_2

CO_2 Contrast due to Age of Stratospheric Air

The concentration of CO_2 in the stratosphere will be lower than in the troposphere by ~ 2 ppm for each year it lags behind due to interannual growth of tropospheric CO_2



Waugh and Hall (2002), Age of stratospheric air: theory, observations and models, Rev. Geophys., 40, 1010, doi:10.1029/2000RG000101

Age of stratospheric air vs latitude as a function of altitude

- **In-situ observations only taken in NH, thus the schematic is symmetrical**
- **AIRS retrievals agree with in-situ measurements in NH and may indicate slight asymmetry**

(Waugh and Hall mirrored the NH result to the SH, where no data existed)

National Aeronautics and
Space Administration

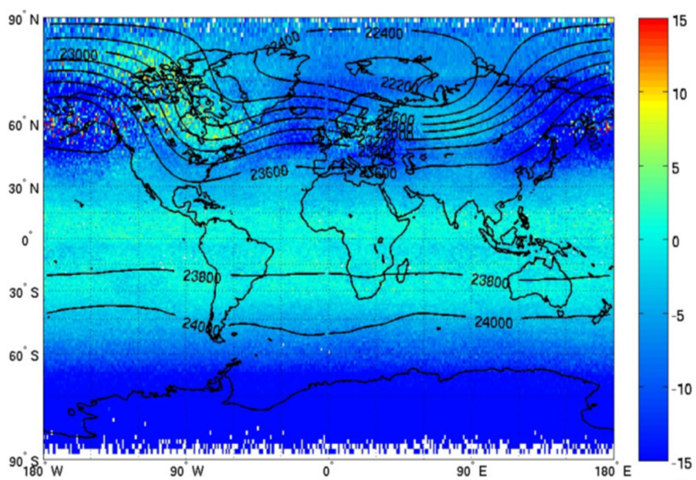
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Atmospheric Infrared Sounder

Stratospheric CO_2 Variation with Latitude
(CO_2 after subtracting $\langle CO_2 \rangle$ for $|lat| \le 4°$)

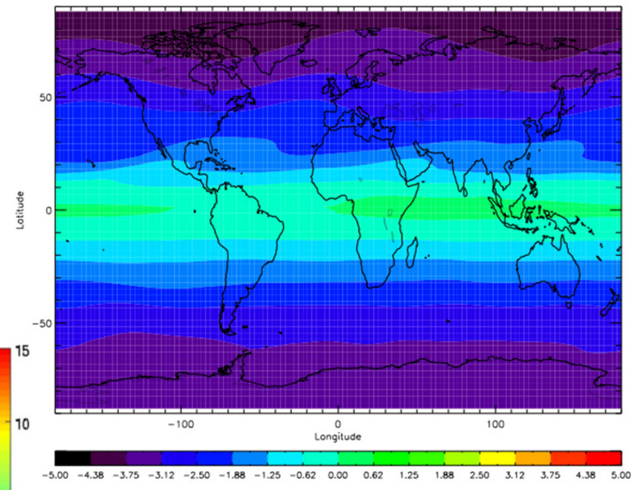
<u>Equator to Pole Contrast</u>
- Models show much lower contrast than AIRS and in-situ measurements

AIRS



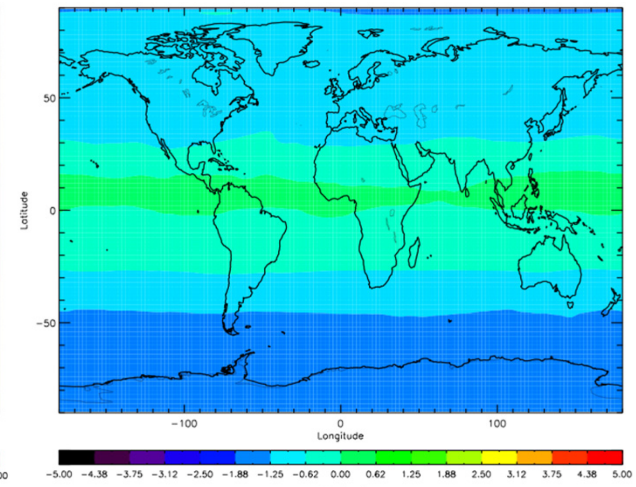
Color Bar Range : -15 to + 15 ppm
Range of Observed Variations: -10 to +5 ppm

3-D IMATCH



Range of Variations: -5 to +2 ppm

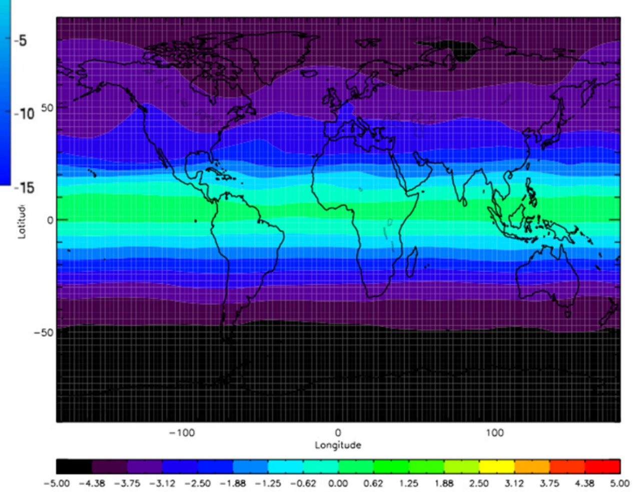
3-D GEOS-Chem



Range of Variations: -2 to +2 ppm

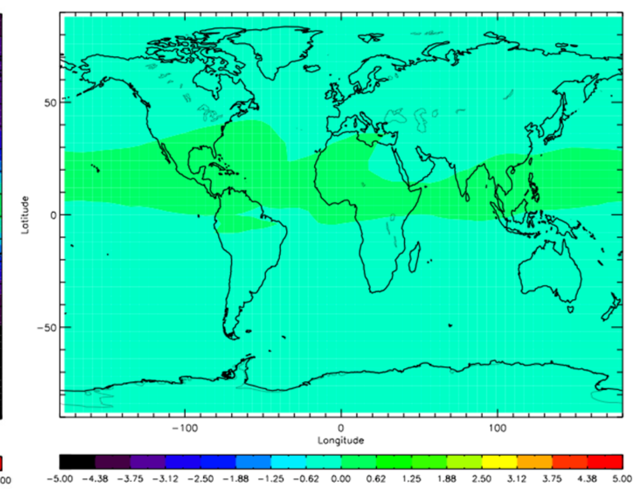
Color Bar Range: -5 to +5 ppm

3-D MOZART-2



Range of Variations: -5 to +2 ppm

3-D Carbon Tracker



Range of Variations: -1 to +2 ppm

AIRS First Results
Lower-Tropospheric CO_2
(2.2km)

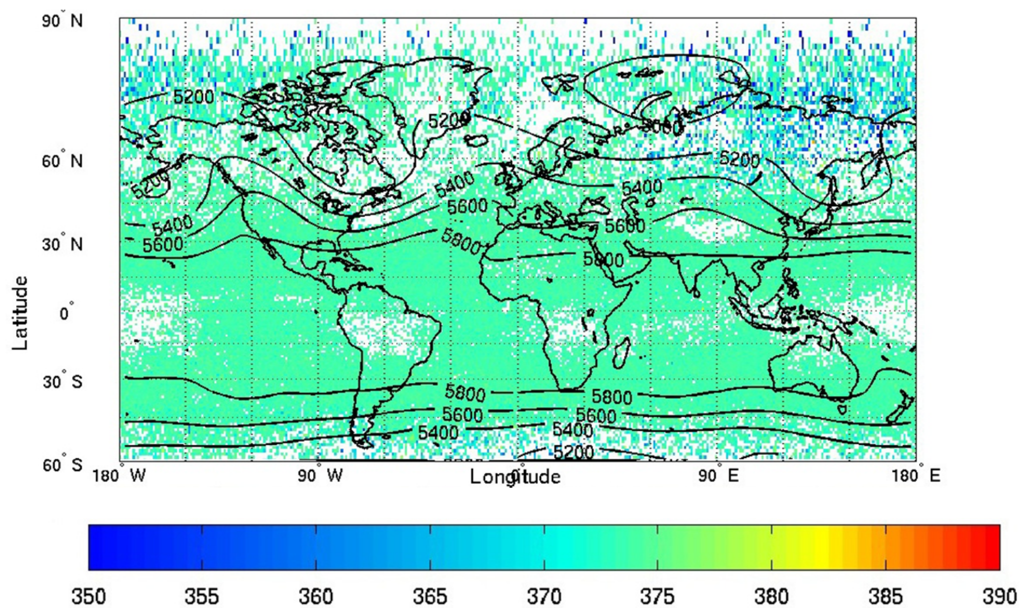
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

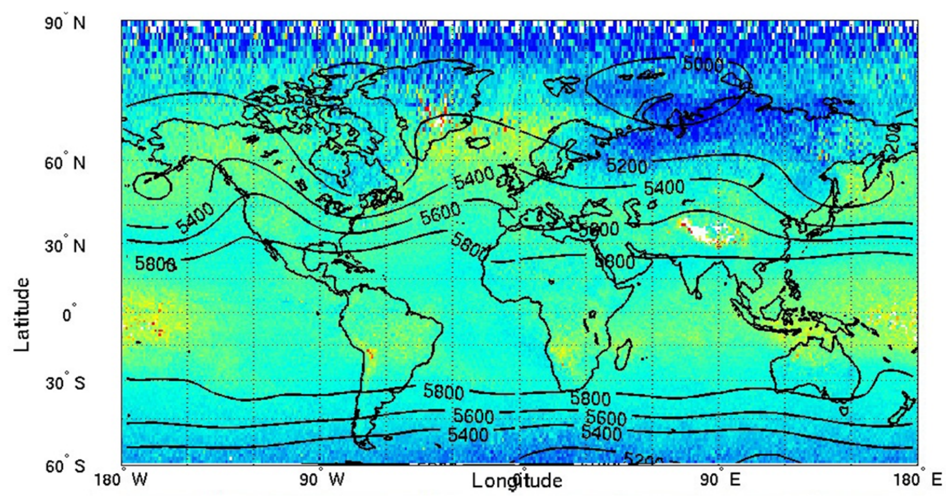
Atmospheric Infrared Sounder

AIRS Lower-Trop (2.2km) vs Mid-Trop CO_2

Mid-Trop - January 2003



Lower-Trop - January 2003



Surface Emission, E_s not yet implemented and no QA applied

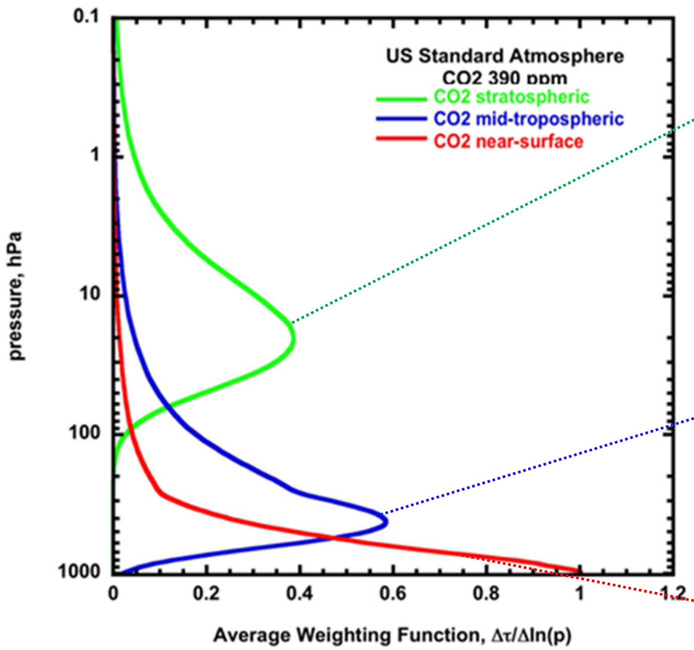
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Atmospheric Infrared Sounder

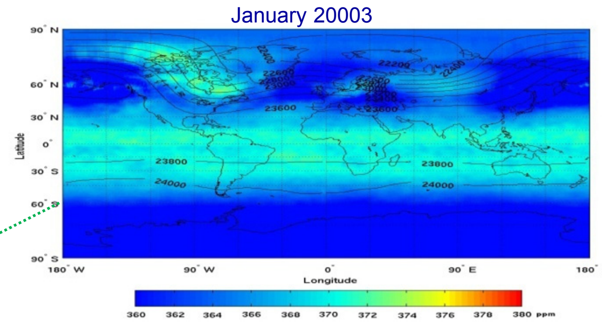
3 Layers of CO_2 Derived from AIRS

Summary



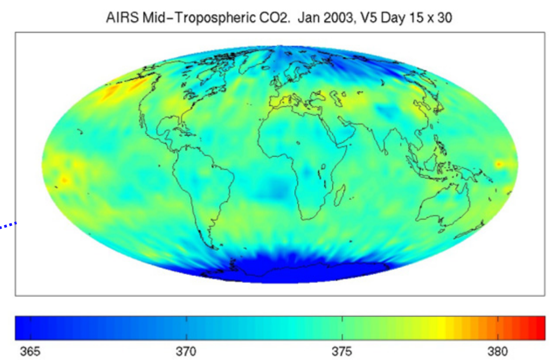
Sensitivity of AIRS Channels to CO2

Stratosphere



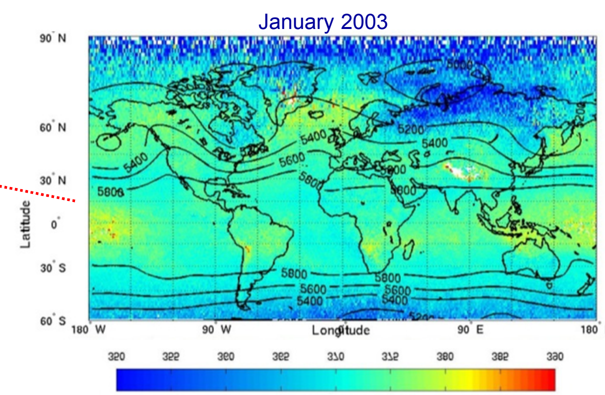
Preliminary

Mid-Troposphere



Complete
Sept 02 - Present

Lower Trop



Preliminary

M. Chahine et. al. (JPL)

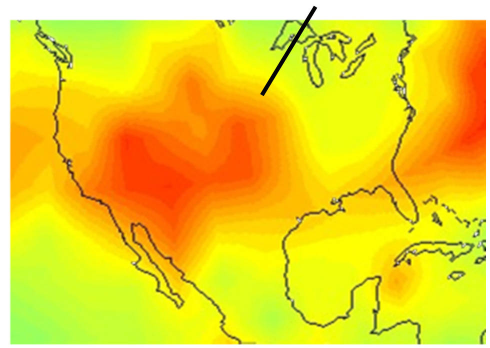
ARIES can map GHG emissions from large cities and counties?

ARIES Characteristics:
- Extension of AIRS Methodology
- Global Maps Daily (±55° Swath)
- Spatial Resolution: 2 km
- Spectral Range: 3.0 – 15.4 μm
- Spectral Resolution: 0.5 cm^{-1}

Over 5000 Channels

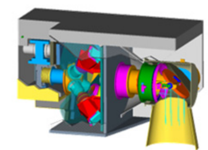
Products: Vertical Profiles of, T, H_2O CO_2, CH_4 CO, N_2O, SO_2, HNO_3, O_3

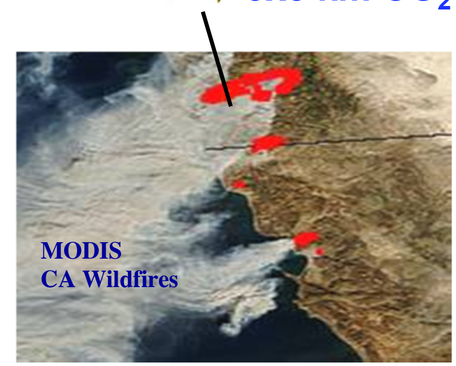
AIRS
14 km
45 km CO_2



AIRS CO_2 Map, July 2003

ARIES
1 km
3x3 km CO_2





ARIES CO_2 Map Resolution

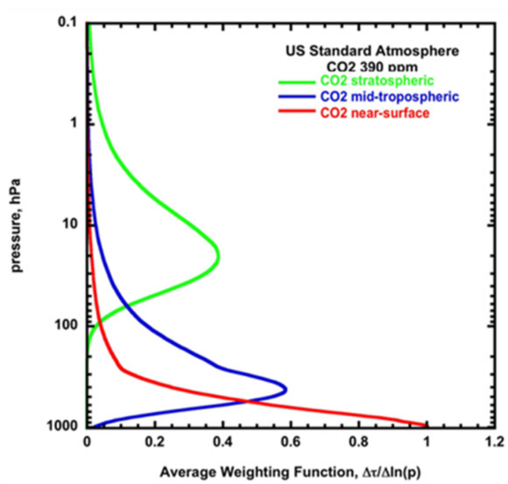
Products	IFOV (km)	λ_1 (μm) ν_1 (cm^{-1})	λ_2 (μm) ν_2 (cm^{-1})	R,$\Delta\nu$ (cm^{-1})
Temperature, CO_2,CH_4,N_2O,CO	1	3.39 2950	4.76 2100	2.0
Water, CH_4, SO_2, HNO_3	1	6.20 1613	8.70 1150	1.0
O_3, HNO_3	1	8.70 1150	11.36 880	0.5
Temperature, CO_2	1	11.36 880	15.38 650	0.5

END

Factors Affecting the CO_2 Retrievals

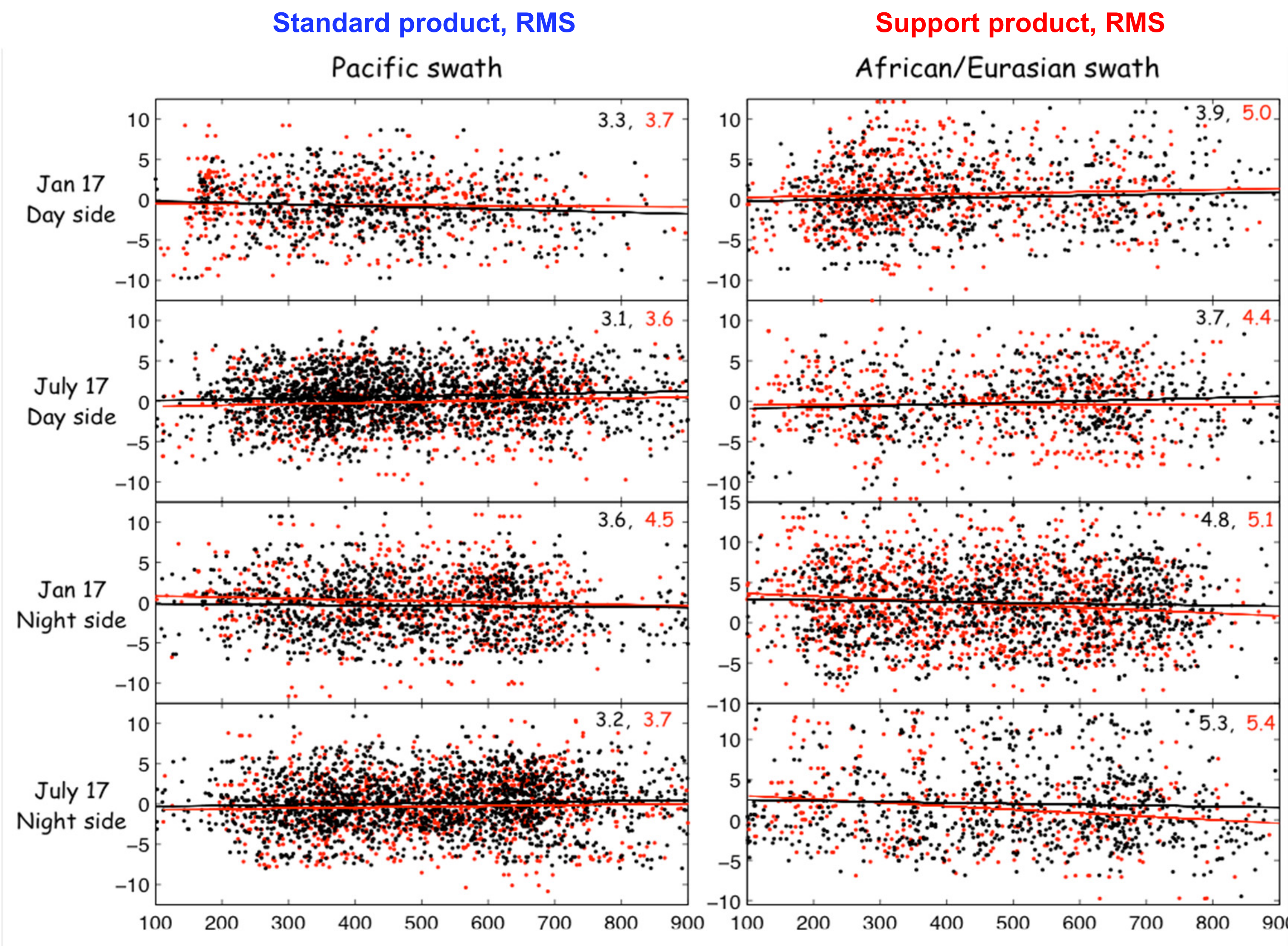
ν range:	Mid-Troposphere -*10km* 13 CO_2 channels: 700 cm^{-1} – 722 cm^{-1}	Stratosphere – *30km* 17 CO_2 channels: 650 cm^{-1} – 680 cm^{-1}	Lower Trop – *2.2km* 10 CO_2 channels: 730 cm^{-1} – 745 cm^{-1}
$T(p)$	Strong	Very strong	Strong
O_3	Strong	Weak	Medium
H_2O	Medium	No impact	Medium
Surface emission, E_s (T_s, ε_s)	Very weak	No impact	Medium
$\Delta G/\Delta CO_2$*	~0.4	~0.2	~0.5

*($\Delta G/\Delta CO_2$) describes the sensitivity of observed spectra to changes in CO_2. It is a function of the lapse rate of atmospheric temperature profiles which is 7 K/km in the mid-troposphere, 1.5K/km in the stratosphere and 10K/km near surface.



- Mid-troposphere: Operational and Released to the Public (Sept 2002 – Present)
- Stratosphere: Algorithm Completed, QA and Validation Underway (8/2010)
- Lower troposphere: Algorithm Nearly Complete, Preliminary Retrievals Underway (12/2010)

AIRS - CarbonTracker upper-tropospheric CO_2 difference [ppm] vs. cloud top pressure eight N/S swaths, 2008



Davis Baker AGU 2010

Finding the LOCAL minimum on an N-Dimensional Surface According to Gauss, Lower Troposphere

The CO_2 retrieval is a post-processing algorithm applied after AIRS Level-2 product generation:

Local Minimum: $\Theta_M,\ T^0(p),\ q^0(p),\ O_3^0(p),\ E_s^0(v)$

$$G^{(n)}(\mathbf{X}) = \sum_{v} \left[\Theta_M(\mathbf{X},v) - \Theta_C^{(n)}(\mathbf{X},v)\right]^2$$

$$\frac{\partial G}{\partial X_{CO_2}} \to 0$$ **Implemented**

$$\frac{\partial G}{\partial X_{T(p)}} \to 0$$ **Implemented**

$$\frac{\partial G}{\partial X_q} \to 0$$ **Implemented**

$$\frac{\partial G}{\partial X_{O_3}} \to 0$$ **Implemented**

$$\frac{\partial G}{\partial X_{E_s}} \to 0$$ **In Progress**

GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L22803, doi:10.1029/2005GL024165, 2005

On the determination of atmospheric minor gases by the method of vanishing partial derivatives with application to CO_2

M. Chahine,[1] C. Barnet,[2] E. T. Olsen,[1] L. Chen,[1] and E. Maddy[3]

Received 22 July 2005; revised 3 October 2005; accepted 11 October 2005; published 18 November 2005.

[1] We present a general method for the determination of minor gases in the troposphere from high spectral resolution observations. In this method, we make use of a general property of the total differential of multi-variable functions to separate the contributions of each individual minor gas. We have applied this method to derive the mixing ratio of carbon dioxide in the mid-troposphere using data from the Atmospheric Infrared Sounder (AIRS) currently flying on the NASA Aqua Mission. We compare our results to the aircraft flask CO_2 measurements obtained by H. Matsueda et al. over the western Pacific and demonstrate skill in tracking the measured 5 ppmv seasonal variation with an accuracy of 0.43 ± 1.20 ppmv. **Citation:** Chahine, M., C. Barnet, E. T. Olsen, L. Chen, and E. Maddy (2005), On the determination of atmospheric minor gases by the method of vanishing partial derivatives with application to CO_2, *Geophys. Res. Lett.*, *32*, L22803, doi:10.1029/2005GL024165.

2. General Approach

[3] We consider the radiative transfer equation

$$R(\nu) = S_s(\nu, \varepsilon_s, \ldots) + \int_{p_s}^{0} B[\nu, T(p)] \left(\frac{\partial \tau(\nu, p, \langle \ldots \rangle)}{\partial p} \right) dp \qquad (1)$$

where $R(\nu)$, the outgoing radiance at frequency ν measured at the satellite, is the sum of emissions from the surface and the atmosphere. Here ε_s is the surface emissivity, B the Planck blackbody function, τ the transmission function from any pressure level p to the top of the atmosphere and the angle bracket $\langle \ldots \rangle$ denotes a function of the profiles of temperature T(p), water vapor q(p), ozone O_3(p), carbon dioxide mixing ratio CO_2(p), etc. In this paper, we express the outgoing radiance $R(\nu)$ in brightness temperature units,

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Atmospheric Infrared Sounder

Multiple Methods have been employed to Determine CO_2 from AIRS Observations

GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L17106, doi:10.1029/2004GL020141, 2004

Midtropospheric CO_2 concentration retrieval from AIRS observations in the tropics

C. Crevoisier, S. Heilliette, A. Chédin, S. Serrar, R. Armante, and N. A. Scott
Laboratoire de Météorologie Dynamique, C.N.R.S., I.P.S.L., Palaiseau, France

Received 1 April 2004; revised 16 July 2004; accepted 2 August 2004; published 4 September 2004.

[1] Midtropospheric carbon dioxide (CO_2) concentration is retrieved in the tropics [20S:20N], over sea, at night, for the period April to October 2003 from the Atmospheric Infrared Sounder (AIRS) observations. The method relies on a non-linear regression inference scheme using neural networks. A rough estimate of the mean precision of the method is about 2.5 ppmv (0.7%). The retrieved seasonal cycle and its latitudinal dependence agree well with aircraft CO_2 in situ measurements made at the same altitude range. Maps produced on a monthly basis at a resolution of 15° × 15°, although not yet fully understood, show good agreement with known characteristics of CO_2 distribution reflecting both atmospheric transport and surface fluxes (fossil fuel emissions, biomass burning, air-surface gas exchanges). *INDEX TERMS:* 0325 Atmospheric Composition and Structure: Evolution of the atmosphere; 0330 Atmospheric Composition and Structure: Geochemical cycles; 1610 Global Change: Atmosphere (0315, 0325); 1640 Global Change: Remote sensing. **Citation:** Crevoisier, C., S. Heilliette, A. Chédin, S. Serrar, R. Armante, and N. A. Scott (2004), Midtropospheric CO_2 concentration retrieval from AIRS observations in the tropics, *Geophys. Res. Lett.*, *31*, L17106, doi:10.1029/2004GL020141.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, D11301, doi:10.1029/2007JD009402, 2008

Click Here for Full Article

CO_2 retrievals from the Atmospheric Infrared Sounder: Methodology and validation

E. S. Maddy,[1] C. D. Barnet,[2] M. Goldberg,[2] C. Sweeney,[3] and X. Liu[1]

Received 19 September 2007; revised 26 December 2007; accepted 30 January 2008; published 3 June 2008.

[1] In this paper we describe the methodology of an offline retrieval of CO_2 from AIRS data and show comparisons of these retrievals with all available NOAA ESRL/GMD aircraft data during 2005. In general, we find that when compared to the aircraft the AIRS CO_2 estimates agree to approximately ±0.5% in middle-tropospheric CO_2 column abundances between ±65 degrees latitude.

Citation: Maddy, E. S., C. D. Barnet, M. Goldberg, C. Sweeney, and X. Liu (2008), CO_2 retrievals from the Atmospheric Infrared Sounder: Methodology and validation, *J. Geophys. Res.*, *113*, D11301, doi:10.1029/2007JD009402.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, D18302, doi:10.1029/2007JD009713, 2008

Click Here for Full Article

A 4-year zonal climatology of lower tropospheric CO_2 derived from ocean-only Atmospheric Infrared Sounder observations

L. Larrabee Strow[1] and Scott E. Hannon[1]

Received 14 December 2007; revised 18 March 2008; accepted 29 May 2008; published 20 September 2008.

[1] A 4-year zonally averaged climatology of atmospheric CO_2, ocean only, between ±60° latitude has been derived from the Atmospheric Infrared Sounder (AIRS) radiances. Using only very clear fields of view, the CO_2 profile in the computed radiances is scaled until agreement is found with observations. ECMWF forecast and analysis fields are used for the temperature profile in the computed radiances. The AIRS channels used to derive CO_2 amounts are nominally sensitive to CO_2 variability in the ~300–800 mbar region (2–9 km), significantly lower in the atmosphere than that in previous studies using AIRS. Validation using aircraft measurements of CO_2 at 650 mbar indicates that the AIRS CO_2 results presented here are accurate to the 0.5–1.0 ppm level. The AIRS-derived climatology clearly exhibits the CO_2 rectifier effect, with mean CO_2 values several parts per million lower than in those in the boundary layer. The AIRS CO_2 seasonal cycle has a relatively constant amplitude of ~3 ppm from +10° to +60° latitude, which matches the boundary layer seasonal cycle amplitude near +10° latitude but is about three times smaller than that in the boundary layer amplitude at +60° latitude. Phase comparisons between the AIRS and boundary layer CO_2 seasonal cycles show the boundary layer phase leading AIRS in the Northern Hemisphere until ~+10° latitude, where the phases cross and the AIRS higher-altitude CO_2 begins to lead the boundary layer phase down to ~−10° latitude. These results may offer new insight into CO_2 interhemispherical transport. Growth rates derived from the AIRS CO_2 climatology are 2.21 ± 0.24 ppm/year, in good agreement with in situ measurements.

Citation: Strow, L. L., and S. E. Hannon (2008), A 4-year zonal climatology of lower tropospheric CO_2 derived from ocean-only Atmospheric Infrared Sounder observations, *J. Geophys. Res.*, *113*, D18302, doi:10.1029/2007JD009713.

ECMWF column estimation via 4D-Var data assimilation system

C. Crevoisier, Heilliettte, S., Chedin, A., Serrar, S., Armante, R., Scott, N.A. (2004), Midtropospheric CO2 concentration retrieval from AIRS observations in the tropics, Geophys. Res. Lett., 31, L17106, doi: 10.1029/2004GL020141.

NOAA regularized nonlinear least squares to minimize $\Sigma(\text{Obs-Calc})^2$

E.S. Maddy, Barnet, C.D., Goldberg, M., Sweney, C., Liu, X. (2008), CO2 from the Atmospheric Infrared Sounder: Methodology and validation, J. Geophys. Res., 113, D11301, doi: 10.1029/2007JD009402.

UMBC remaining radiance residuals for nighttime clear ocean fields

L. L. Strow, Hannon, S.E. (2008), A 4-year zonal climatology of lower tropospheric CO2 derived from ocean-only Atmospheric Infrared Sounder observations, J. Geophys. Res., 113, D18302, doi: 10.1029/2007JD009713.